(E84-10056) RADIOMETRIC CALIBRATION AND PROCESSING PROCEDURE FOR REFLECTIVE BANDS ON LANDSAT-4 PROTOFLIGHT THEMATIC MAPPER (NASA) 40 p HC A03/MF A01 CSCL 08B

N84-31731

Unclas
G3/43 00056

RADIOMETRIC CALIBRATION AND PROCESSING PROCEDURE FOR REFLECTIVE BANDS ON LANDSAT-4 PROTOFLIGHT THEMATIC MAPPER

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RADIOMETRIC CALIBRATION AND PROCESSING PROCEDURES FOR REFLECTIVE BANDS ON LANDSAT-4 PROTOFLIGHT THEMATIC MAPPER

ABSTRACT

This paper provides descriptive and procedural background material for understanding results that are given in the following papers by Barker et al. appearing in these Proceedings: "Prelaunch Absolute Radiometric Calibration of the Reflective Bands on the Landsat-4 Protoflight Thematic Mapper," "Characterization of Radiometric Calibration of Landsat-4 TM Reflective Bands," "TM Digital Image Products for Applications," and "Relative Radiometric Calibration of Landsat-4 TM Reflective Bands."

The radiometric subsystem of NASA's Landsat-4 Thematic Mapper (TM) sensor is described. Special emphasis is placed on the internal calibrator (IC) pulse shapes and timing cycle. The procedures for the absolute radiometric calibration of the TM channels with a 122-centimeter integrating sphere and the transfer of radiometric calibration from the channels to the IC are reviewed.

The use of the IC to calibrate TM data in the ground processing system consists of pulse integration, pulse averaging, IC state identification, linear regression analysis, and histogram equalization. An overview of the SCROUNGE-era (before August 1983) method is presented. Procedural differences between SCROUNGE and the TIPS-era (after July 1983) and the implications of these differences are discussed.

KEY WORDS: absolute calibration, relative calibration, band-to-band calibration, internal calibration system, SCROUNGE, TIPS, scan cycle timeline, Thematic Mapper, Landsat-4

INTRODUCTION

Absolute calibration is essential for a variety of scientific studies and image analysis applications. Arithmetic spectral transformations, such as those used to determine path radiance for removal or normalization of atmospheric effects, require absolute radiometric data. To extend signatures, based on averages or moments, beyond a scene, to data collected in different scenes or at different times under different atmospheric conditions, or even to data collected by different satellites, requires both an absolute measure of radiance and correction for atmospheric effects.

Understanding the innate bidirection reflectance characteristics of the target depends on exact knowledge of reflected radiance. To evaluate theoretical models that relate spectral radiance to ground and/or atmospheric parameters, numerical values for radiance are necessary.

To achieve absolute radiometric accuracy, frequent in-orbit recalibration of the sensor system is necessary. The Landsat-4 Thematic Mapper (TM) meets this need with an internal calibration (IC) system based on incandescent lamps controlled by photodiode incandescent circuits. The IC system itself, however, is not immune to changes with time. Frequent recalibration by a constant external source, such as the Sun, would increase the absolute radiometric accuracy. Use of the IC can provide relative radiometric accuracy, which is essential to eliminate striping and to delineate boundaries.

This paper describes the prelaunch absolute radiometric calibration procedures and the relative radiometric calibration procedures in the postlaunch ground processing of the six reflective bands. Both SCROUNGE and TIPS (TM Image Processing System) methodologies are discussed. Lyons et al. (1984) present an overview of the entire SCOUNGE system, with special emphasis on geometric correction procedures. Lansing and Barker (1984) describe the calibration procedures for the thermal band (band 6).

THEMATIC MAPPER RADIOMETRIC SUBSYSTEM

This section briefly reviews background essential to this paper and characterizes raw data obtained from the IC system. Engel (1980) describes the TM in detail.

The TM observes radiance reflected from the Earth's surface in six bands of the following wavelengths: 0.45 to 0.52 μm, 0.52 to 0.60 μm, 0.63 to 0.69 μm, 0.76 to 0.90 μm, 1.55 to 1.75 μm, and 2.08 to 2.35 μm. Each band comprises 16 detectors that create 16 raster lines as the ground is scanned in a cross-track direction. Data are collected during the full cycle of the scan mirror rotation resulting in both west-to-east and east-to-west scans. In descending orbits (daytime), west-to-east scans are known as forward scans and east-to-west scans, as reverse scans; in ascending orbits, the converse occurs. The 64 silicon detectors that form the first four bands reside in the primary focal plane. The indium antimonide detectors used for the remaining two reflective bands, bands 5 and 7, reside in a cooled focal plane. On each band, the eight even-numbered detectors lie in a separate row, staggered from the odd-numbered detectors, and

have separate electronic connections. Figures 1 and 2 show the path that light travels within the TM.

The IC consists of three miniature tungsten filament lamps for the reflective bands, a blackbody for the thermal band, and a flex pivot-mounted resonant shutter. The IC inserts reference radiance levels just ahead of the spectral filters of each band at the prime focal plane while obscuring the Earth view of the detector array. To do this correctly, the IC shutter flag motion must be synchronized with that of the scan mirror assembly and the scan line corrector. (Engel (1980) gives a description of these subsystems.) Figure 3 is an overview of the IC shutter flag and transfer optics. Figure 4 illustrates the optics for the three lamps.

Figure 5 is a scaled schematic timeline of a TM scan cycle showing the time periods during which the detectors observe the target image and during which the shutter flag obscures the image during scan mirror turnaround. It should be noted that the image obscuration time is subdivided into a dark period for the collection of background data and a period during which the radiance from the calibration lamps is in view. During 3 milliseconds of the dark period, the background radiation is adjusted to approach preset values. Tables 1 and 2 show all events on the TM scan timeline for a forward and a reverse scan.

The lamps in the IC operate at 1900 K, with the amplitude of each lamp in the normal mode controlled by a silicon photodiode in a feedback circuit to maintain a constant radiance level. (A backup mode that does not maintain the lamp radiance level is also available; with lamp aging, the backup mode will not provide stable lamp levels). The IC lamps, with energy balance filters and masks, output at levels reduced by 0, 25, and 50 percent (see Figure 4). A bundle of six fiber optic threads delivers the combined lamp output to the shutter flag. This method of transmitting radiation to the moving calibration shutter allows the lamps to provide radiation independently and to contribute proportionately toward illuminating all detectors. When in the automatic sequencing mode, the three lamps are cycled automatically to provide eight calibration levels (seven plus dark) to all detectors of bands 1 through 5 and 7. Each level is on for approximately 40 scans. In this paper, lamp configuration is indicated by three binary digits (that is, 100 means lamp A is on and B and C are off, 011 means only B and C are on, and so on).

The shape of the pulse output by the internal calibration system depends on the physical location of the detector with respect to the calibration light source. Detectors are

FIGURE 1

Landsat-4 Thematic Mapper (TM)
Optical Path

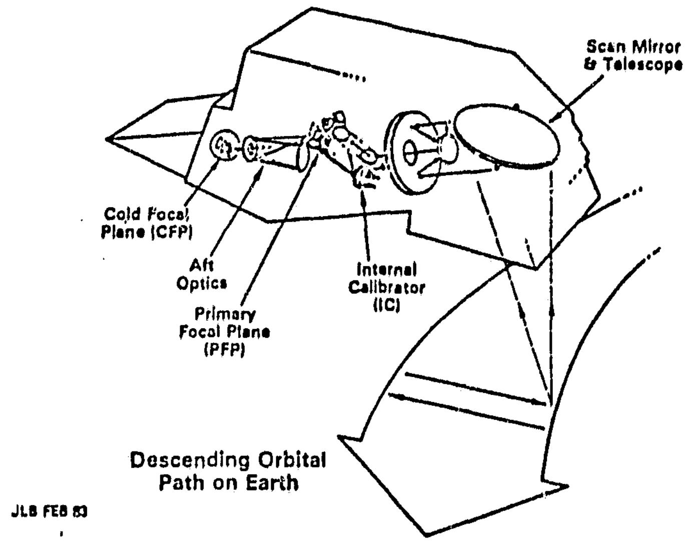

FIGURE 2

TM Optical Path
Landsat-4 Thematic Mapper

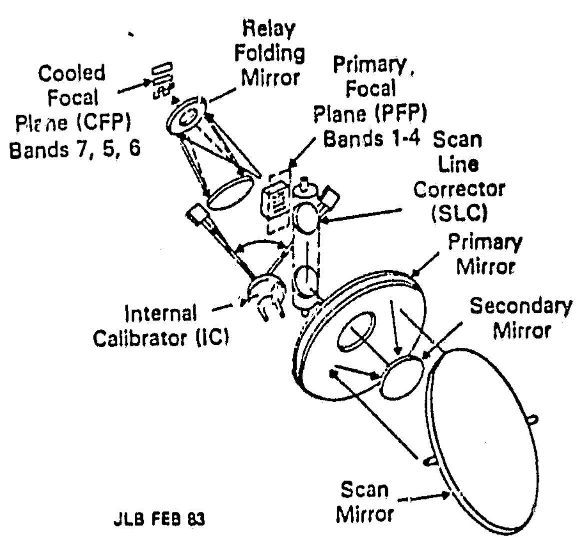

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FIGURE 3

LANDSAT-4 THEMATIC MAPPER INTERNAL CALIBRATION TRANSFER OPTICS

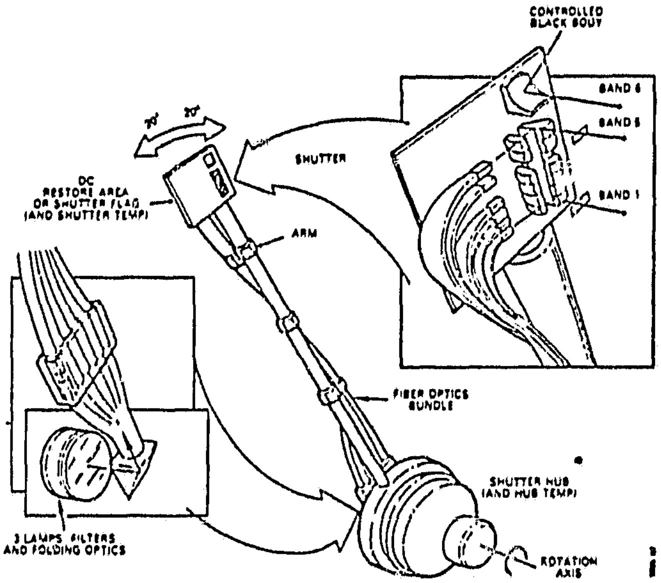

FIGURE 4

LANDSAT-4 THEMATIC MAPPER INTERNAL CALIBRATION THREE LAMP OPTICS

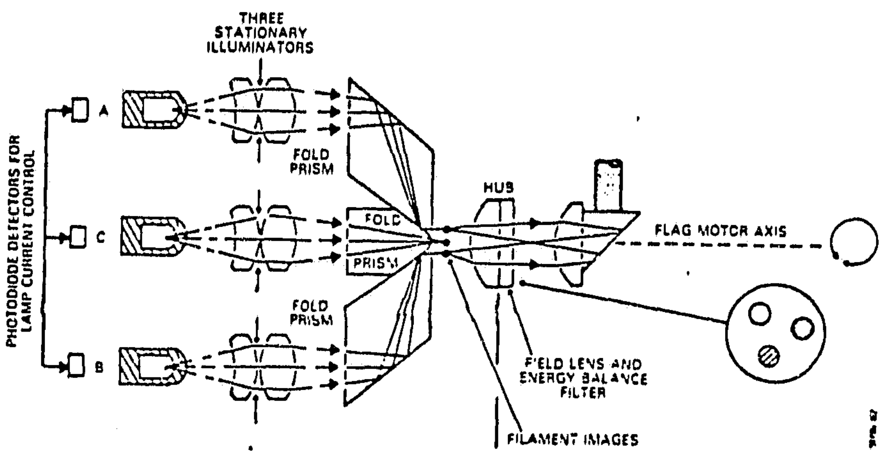

FIGURE 5

DIGITAL MINOR FRAME LOCATIONS FOR SUCCESSIVE TM SCANS

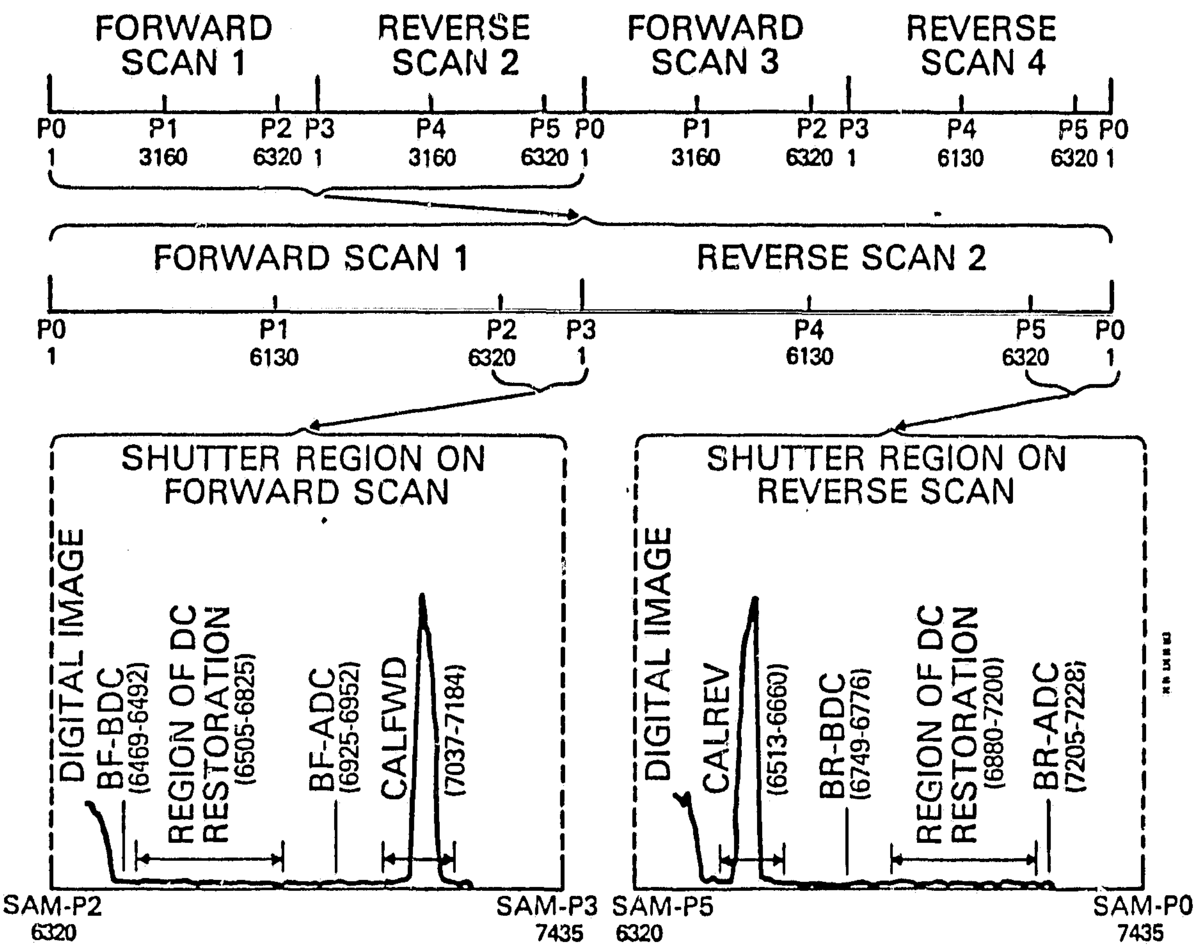

Table 1
Timing Locations on Main Shutter during Odd Numbered (Forward) Scans of Internal Calibrator (IC) on Landsat-4 Thematic Mapper and Scrounge-ERA (1982-1983) Ground Processing IC Collect Windows

Collect Window Label	Location From Start of Line (mf)	Location From Start of Line (msec)	Minor Frame Label	Description of Label	Method of Calculating Location (2)	
(1)	(2)	(3)				
	1	0.00	P0	SAM SOL (Scan Angle Monitor FWD Start)	DEF	Start of mf Counting in ADDS
	3160	30.37	P1	SAM Midpoint of Active FWD Scan	NOM	From Scan Mirror Frequency
	6320	60.74	P2	SAM EOL End of Active FWD Scan	NOM	From Scan Mirror Frequency
	6383	61.35	EOIF16	End of Image (FWD) for CH 16	CALC	SOSF16-16= SOSF1-70
	6399	61.50	SOSF16	Start of IC Shutter (FWD) for CH 16	CALC	SOSF1-[(CALF1-CALF16) =54]
	6407	61.58	SADDSF	Start of 824mf ADDS FWD "MAP1" Buffer	DEF	
	6437	61.87	EOIF1	End of Image (FWD) for CH 1	CALC	SOSF1-16
	6453	62.02	SOSF1	Start of Shutter (FWD) for CH 1	OBS	ADDS Comtal of 2 NOV 82 Data
BF-BDC	6469	62.17	SBFBDC	Start of 24mf ADDS FWD BKGD Before DC	CALC	(Multiple of 4) +1 of(MBFBDC-12)
BF-BDC	6479	62.27	MBFBDC	Middle of ADDS FWD BKGD Before DC	CALC	(SOSF1 + SODCF) / 2
BF-BDC	6492	62.39	EBFBDC	End of 24mf ADDS FWD BDGD Before DC	CALC	SBFBDC + 24-1
	6505	62.52	SODCF	Start of DC Restore Region for FWD Scan	CALC	1.023 msec (106mf) to SOSF16
	6825	65.60	EODCF	End of DC Restore Region for FWD Scan	CALC	3.075 msec (320mf) to SODCF
BF-ADC	6925	66.56	SBFADC	Start of 28mf ADDS FWD BKGD After DC	CALC	(Multiple of 4)+1 of(MBFADC-14)
BF-ADC	6938	66.68	MBFADC	Middle of ADDS FWD BKGD After DC	CALC	(CALF16-32+EODCF) / 2
BF-ADC	6952	66.82	EBFADC	End of 28mf ADDS FWD BKGD After DC	CALC	SBFADC + 28 - 1
CALFWD	7037	67.63	SCALF	Start of 148mf ADDS CAL FWD Collect	DEF	Starting 20 May 83
CALFWD	7084	68.08	CALF16	Center of CAL FWD Pulse for CH 16	OBS	TRAPP (4) for 2 NOV 82 Scene
CALFWD	7109	68.32	CALF9	Center of CAL FWD Pulse for CH 9	OBS	TRAPP (4) for 2 NOV 82 Scene
CALFWD	7111	68.34	MCALF	Middle of CAL FWD Region	CALC	(CALF16 + CALF1) / 2
CALFWD	7112	68.35	CALF8	Center of CAL FWD Pulse For CH 8	OBS	TRAPP (4) for 2 NOV 82 Scene
CALFWD	7138	68.60	CALF1	Center of CAL FWD Pulse for CH 1	OBS	TRAPP (4) for 2 NOV 82 Scene
CALFWD	7184	69.05	ECALF	End of 148mf ADDS CAL FWD Collect	CALC	SCALF + 148-1
	7182	69.03	EOSF16	End of IC Shutter (FWD) for CH 16	OBS	ADDS Comtal of 2 NOV 82 Data
	7198	69.18	SOIR16	Start of Image Before REV Scan for CH 1	CALC	EOSF16 + 16
	7230	69.49	EADDSF	End of 824mf ADDS FWD "MAP1" BUFFER	DEF	
	7236	69.55	EOSF1	End of Shutter (FWD) for CH 1	CALC	EOSF16 + 54
	7252	69.70	SOIR1	Start of Image Before REV Scan for CH 1	CALC	EOSF1 + 16
	7435	71.46	P3	SAM SOL (Scan Angle Monitor REV Start)	CALC	71.46 msec/.009611 msec/mf

FOOTNOTES FOR TABLE 1
MF LOCATIONS FOR ODD-NUMBERED (FORWARD) SCANS

(1) Collection of digital data for radiometric calibration of TM during the Scrounge-Era preprocessing by ADDS, 824mf (minor frames) of IC (Internal Calibrator) data are temporarily put in a buffer of a Macro Array Processor (MAP1). These calibration data are collected starting at minor frame 6407, which is close to the end of the scene video data and the beginning of shutter obscuration. 200 of the 824mf are sent on to a Vax computer for use in radiometric calibration.

For odd-numbered scans (forward sweeps of the TM scan mirror), these 200mf from the IC shutter are collected from three separate regions (windows). Labels and descriptions for the three collect windows from each forward scan are given below:

BF-BDC This is a 24mf region of dark level background (BKG) taken on a forward scan before DC restoration begins. Prior to May 20, 1983, there was a single 52mf ADDS BKG collect window which started before DC restoration, at MF 6543.

BF-ADC 28mf BKG taken after DC forward restoration ends.

CALFWD This is a 148mf forward scan calibration (CAL) region containing the TM responses to light from the current configuration of the three IC lamps. Prior to December 22, 1982, the 148mf CAL collect window started at MF 7009. It then began at MF 7029 until May 20, 1983, when it was changed to MF 7037.

(2) MF (Minor Frame) locations were arrived at one of four ways:

DEF By Definition

NOM From nominal value of another variable

OBS Observed from in-orbit digital data

CALC Calculated from values of other MF locations and defined, nominal or observed relative differences

(3) MSEC (Milliseconds) locations were calculated from MF locations assuming a nominal 9.611 microseconds per minor frame.

(4) TRAPP is a TM Radiometric and Algorithmic Performance software program run on pre and postlaunch tapes at the LAS Facility.

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Table 2
Timing Locations on Main Shutter during Even Numbered(Reverse) Scans of Internal Calibrator (IC) on Landsat-4 Thematic Mapper and Scrounge-ERA (1982-1983) Ground Processing IC Collect Windows

Collect Window Label	Location From Start of Line (mf)	(msec)	Minor Frame Label	Description of Label	Method of Calculating Location (2)	
(1)	(2)	(3)				
	1	0.00	P3	SAM SOL (Scan Angle Monitor REV Start)	DEF	Start of mf Count
	3160	30.37	P4	SAM Midpoint of Active REV Scan	NOM	From Scan Mirror Frequency
	6320	60.74	P5	SAM EOL (End of Active REV Scan)	NOM	From Scan Mirror Frequency
	6407	61.58	SADDSR	Start of 824mf ADDS REV "MAP1" Buffer	DEF	
	6453	62.02	EOIR1	End of Image (REV) for CH 1	CALC	(SOSR1-12); also OBS Comtal
	6465	62.14	SOSR1	Start of IC Shutter (REV) for CH 1	OBS	ADDS Comtal of 2 NOV 82 Data
	6507	62.54	EOIR16	End of Image (REV) for CH 16	CALC	(SOSR16-12); also OBS Comtal
CALREV	6513	62.60	SCALR	Start of 148mf ADDS CAL REV Collect	DEF	Starting 20 MAY 83
CALREV	6519	62.65	SOSR16	Start of IC Shutter (REV) for CH 16	OBS	ADDS Comtal of 2 NOV 82 Data
CALREV	6560	63.05	CALR1	Center of CAL REV Pulse for CH 1	OBS	TRAPP (4) Data for 2 NOV 82 Scene
CALREV	6580	63.24	CALR8	Center of CAL REV Pulse for CH 8	OBS	TRAPP (4) Data for 2 NOV 82 Scene
CALREV	6587	63.31	MCALR	Middle of CAL REV Region	CALC	(CALR1 + CALR16) / 2
CALREV	6614	63.57	CALR16	Center of CAL REV Pulse for CH 16	OBS	TRAPP (4) Data for 2 NOV 82 Scene
CALREV	6660	64.01	ECALR	End of 148mf ADDS CAL REV Collect	CALC	SCALR + 148-1
BR-BDC	6749	64.86	SBRBDC	Start of 28mf ADDS REV BKGD Before DC	CALC	(Multiple of 4)+1 of (MBRBDC-14)
BR-BDC	6763	65.00	MBRBDC	Middle of REV BKGD Before DC	CALC	(CALR16 + 32 + SODCR) / 2
BR-BDC	6776	65.12	EBRBDC	End of 28mf ADDS REV BKGD Before DC	CALC	SBRBDC + 28-1
	6880	66.12	SODCR	Start of DC Restore Region for REV Scan	CALC	4.098msec (426mf) to EOSR16
	7200	69.20	EODCR	End of DC Restore Region for REV Scan	CALC	3.075msec (320mf) to SODCR
BR-ADC	7205	69.25	SBRADC	Start of 24mf ADDS REV BKGD After DC	CALC	EBRADC - 24 + 1
BR-ADC	7226	69.45	MBRADC	Middle of REV BKGD After DC	CALC	(EODCR + EOSR1) / 2
BR-ADC	7228	69.47	EBRADC	End of 24mf ADDS REV BKGD After DC	CALC	First Multiple of 4 below EADDSR
	7230	69.49	EADDSR	End of 824mf ADDS REV "MAP1" Buffer	DEF	
	7252	69.70	EOSR1	End of IC Shutter (REV) for CH 1	CALC	SOSR1 + 787
	7264	69.81	SOIF1	Start of Image Before FWD Scan for CH 1	CALC	EOSR1 + 12
	7306	70.22	EOSR16	End of IC Shutter (REV) for CH 16	CALC	SOSR16 + 787
	7318	70.33	SOIF16	Start of Image Before FWD Scan for CH 16	CALC	EOSR16 + 12
	7435	71.46	PO	SAM SOL (Scan Angle Monitor FWD Start)	CALC	71.46 msec/.009611 msec/mf

FOOTNOTES FOR TABLE 2
MF LOCATIONS FOR EVEN-NUMBERED (REVERSE) SCANS

(1) Collection of digital data for radiometric calibration of TM during the Scrounge-Era preprocessing by ADDS, 824mf (minor frames) of IC (Internal Calibrator) data are temporarily put in a buffer of a Macro Array Processor (MAP1). These calibration data are collected starting at minor frame 6407, which is close to the end of the scene video data and the beginning of shutter obscuration. 200 of the 824mf are sent on to a Vax computer for use in radiometric calibration.

For even-numbered scans (reverse sweeps of the TM scan mirror), these 200 mf from the IC shutter are collected from three separate regions (windows). Labels and descriptions for the three collect windows from each reverse scan are given below:

CALREV This is a 148mf reverse scan calibration (CAL) region containing the TM responses to light from the current configuration of the three IC lamps. Prior to December 22, 1982, the 148mf CAL collect window started at MF 6525. It then began at MF 6517 intil May 20, 1983, when it was changed to MF 6513.

BR-BDC This is a 28mf region of dark level background (BKG) taken on a reverse scan before DC restoration begins.

BR-ADC 24mf BKG taken after DC reverse restoration ends. This is the same shutter location as the 24mf forward BKG. Prior to May 20, 1983, there was a single 52mf ADDS BKG collect window which started after DC restoration, at MF 7089.

(2) MF (Minor Frame) locations were arrived at one of four ways:

DEF By definition

NOM From nominal value of another variable

OBS Observed from in-orbit digital data

CALC Calculated from values of other MF locations and defined, nominal or observed relative differences.

(3) MSEC (milliseconds) locations were calculated from MF locations assuming a nominal 9.611 microseconds per minor frame.

(4) TRAPP is a TM Radiometric and Algorithmic Performance software program run on pre and postlaunch tapes at the LAS Facility.

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stored by band number in even-numbered and odd-numbered rows; thus even (or odd) numbered channels of a given band have the same pulse shape. Sample pulses are provided in Appendix A (Figures A-1 through A-18); Figure 6 shows a typical pulse. Pulse shape is independent of scan direction. If the pulse from a reverse scan is overlaid on a forward scan pulse, the difference in counts for corresponding positions is at most two digital numbers (DN) (Figures 7 and 8).

Within a given band, the location of the pulse center progresses to higher numbered minor frames as the channel number decreases. Bands 1 and 4 have sharp asymmetric peaks; bands 2 and 3 have rounder, less asymmetric peaks. Bands 1 and 2 have peaks to the right of the pulse center in the forward scan; bands 3 and 4 have peaks to the left of the pulse center. In bands 1 and 2, the odd channels have larger pulses, about 6 counts higher in band 1 and 20 counts higher in band 2. The even channels in bands 3 and 4 have slightly larger pulses than the odd channels, about five counts in band 3 and two counts in band 4. Band 5 even pulses are 38 counts higher than odd pulses. For both even and odd channels, the pulse is asymmetric, peaking to the right of the center, but the odd-channel pulses are much rounder. Although even-channel pulses in bands 6 and 7 are only eight counts greater than odd-channel pulses, the pulse shapes are qualitatively different in the two cases. The even channels have nearly symmetrical rounded pulses, peaking slightly to the right of center. The odd channels have a flat plateau to the left of center, and then a peak to the right.

Figure 9 shows pulse averages, as determined by the Hughes method discussed below, versus scan number for a post-launch scene. It should be noted that transitions involving the turning on of a lamp result in approximately 15-percent overshoot. In mid-IR bands, bands 5 and 7, blackbody heat radiation from the newly turned off lamp contributes to the pulse height for approximately eight scans (four forward and four reverse).

ABSOLUTE RADIOMETRIC CALIBRATION PROCEDURE

Prelaunch absolute radiometric calibration of the TM sensor channels and the IC is critical because the TM does not observe the Sun or other extraterrestrial bodies of known radiance while in orbit. This section presents an overview of prelaunch absolute calibration procedures used on the Landsat-4 TM. A detailed discussion of the results of absolute calibration is presented in Barker et al. (1984a).

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FIGURE 6

RADIOMETRIC CALIBRATION — TM LANDSAT-4
TM1 C8 FORWARD SCAN, MARCH 9, 1982, VACUUM PRELAUNCH

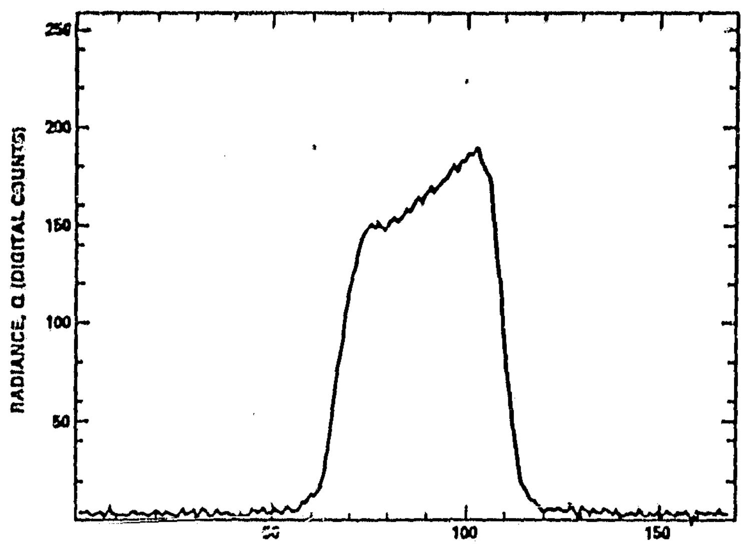

FIGURE 7

COMPARISON OF CALIBRATION PULSES BETWEEN FORWARD
AND REVERSE SCANS PRELAUNCH DATA

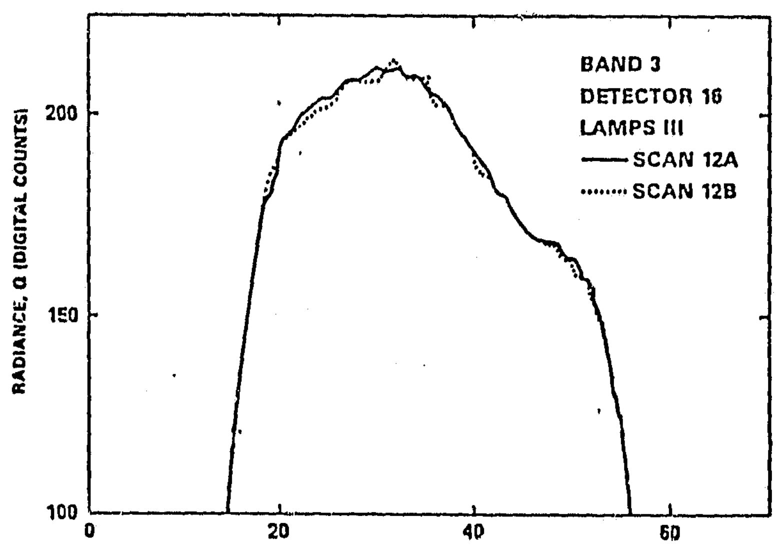

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FIGURE 8

COMPARISON OF CALIBRATION PULSES BETWEEN FORWARD AND REVERSE SCANS
POSTLAUNCH DATA

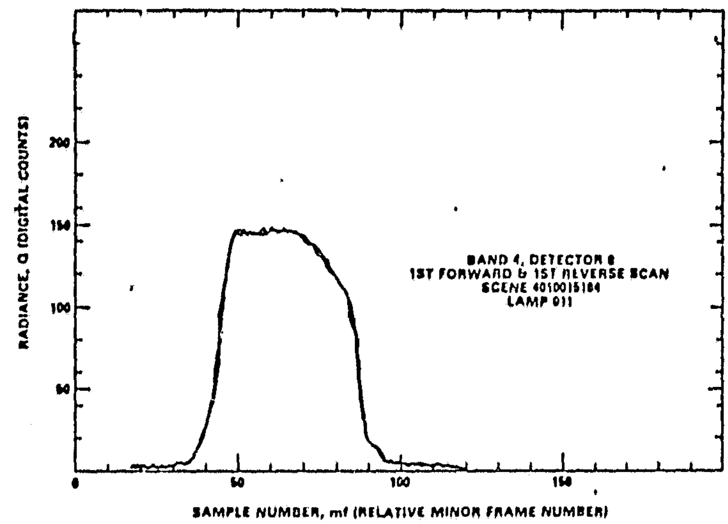
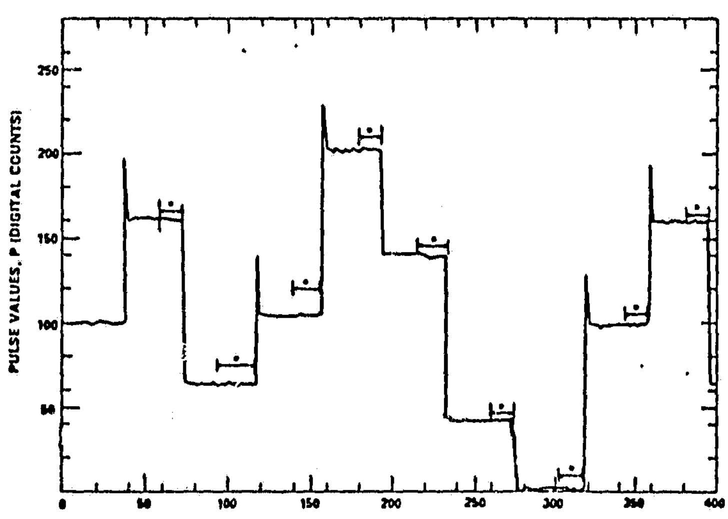


FIGURE 9

POSTLAUNCH RADIOMETRIC CALIBRATION — TM LANDSAT-4
BAND 1 CHANNEL 9



*PULSE VALUES USED IN COMPUTING PULSE AVERAGE, P̄, IN THE SCHOUNGE SYSTEM.

The prelaunch radiometric calibration procedures are designed to ensure that the TM meets its performance requirements. The radiometric specifications can be divided into three groups: dynamic range, sensitivity, and accuracy.

The TM is designed for land observations; the reflective bands are therefore designed for maximum dynamic range for the expected land radiance levels (Fraser, 1975; Duck, 1977). This range can be tested using a well-calibrated external source. The radiometric sensitivity is expressed in terms of signal-to-noise ratio (SNR) for reflective bands. Radiometric accuracy is one of the most important issues to be addressed. The relative accuracy requirements are quite stringent: about 1 quantum level for between-detector accuracy and 2 percent for between-band accuracy. The overall absolute accuracy specified for the TM is 10 percent. Obtaining absolute calibration accuracy for spaceborne instruments has traditionally been a very difficult task.

The calibration procedure used was developed by Hughes Aircraft Company (HAC) to test the performance of the TM channels; to determine the end-to-end radiometric transfer function with 10-percent accuracy; and to verify that the relative radiometric accuracy is better than 2 percent, the within-band accuracy is 1 DN, the SNR is within specification, and the IC is accurate and has the correct range.

CALIBRATION EQUIPMENT

The usual approach to the prelaunch calibration of visible and near-infrared sensors is by comparing them to a secondary source that has been calibrated with a National Bureau of Standards (NBS) standard lamp. The secondary standard used with the TM is a 122-centimeter (diameter) Integrating Sphere (IS(122)) maintained by the National Aeronautics and Space Administration/Goddard Space Flight Center (NASA/GSFC) and HAC Santa Barbara Research Center (SBRC) personnel. SBRC has maintained the IS(122) and has periodically recalibrated it by comparison with a secondary standard lamp using a monochromator. These tests were performed in June 1979 and February 1982 at NASA/GSFC and in June 1980 and May 1982 at SBRC and are discussed by Walker (1982a, 1982b). The secondary standard is related to an NBS standard by a similar calibration procedure.

The IS(122) is a hollow sphere with an inside diameter of 122 centimeters. It consists of two aluminum hemispheres mounted in a framework that allows easy access to the interior for bulb and surface maintenance. A 46-centimeter-diameter aperture allows reflected light from the

12 quartz-halogen standard lamps out of the interior to calibrate the sensor. The inside surface of the sphere is coated with a white diffusely reflecting barium sulfate-based paint (McCullough et al., 1969).

The lamps in the IS(122) have different wattages. There are six 200-watt lamps, two 100-watt lamps, and four 25-watt lamps, for a maximum of 1500 watts. The lamps are operated at derated wattages to prolong their useful lifetimes. During the calibration tests, the lamps are all lighted initially for each test sequence, as shown in Table 3. The lamps are then sequenced off to reach the next lower radiance level. Twenty levels are used in all. The responses of all 96 detectors in the reflective bands (bands 1 through 5 and 7) are noted at each level, and the detector gains, offsets, and SNRs are calculated.

The IS(122) is directly calibrated against a secondary standard lamp that has in turn been calibrated by a standard lamp of similar design and is directly related to an NBS standard. The standard and the secondary lamps are both quartz-halogen 1000-watt lamps. The overall accuracy of these lamps and the complete calibration sequence are discussed in Barker et al. (1984a).

CALIBRATION PROCEDURES FOR THE TM WITH THE IS(122)

Calibration of the TM with a known source, the IS(122), consists of comparing the TM output with the series of known radiances input to the TM from the source. This procedure is designed to determine the overall response of the TM under known conditions.

Each calibration of the IS(122) results in a series of spectral radiance values at intervals of 50 nanometers in wavelength from 400 to 2500 nanometers for each sphere-lamp configuration (combination of particular lamps on) (Walker, 1982b). This spectral radiance output from the IS(122) is then combined with the measured wavelength response of the TM (Markham and Barker, 1984) in each band to obtain the spectral radiance that each TM detector would see in a particular band and for a particular IS(122) lamp configuration.

These radiance levels by band are the known input to the TM for calibration. During each test, the digital output response of the TM to each input level is collected, averaged, and then compared to the known radiance input to obtain the calibration parameters (gain and offset). Figure 10 illustrates a linear fit of digital counts to radiance to determine channel gain (G(C)) and offset (O(C)).

TABLE 3

INTEGRATING SPHERE LAMP CONFIGURATIONS BY RADIANCE LEVEL

TEST SEQUENCE I			TEST SEQUENCE II		
SEQUENCE NUMBER[b]	LAMP CONFIGURATION[a]	NOMINAL LAMP POWER (W)	SEQUENCE NUMBER[b]	LAMP CONFIGURATION[a]	NOMINAL LAMP POWER (W)
1(1)	624	1500	1(6)	224	700
2(2)	524	1300	2(7)	214	600
3(3)	424	1100	3(9)	114	400
4(4)	324	900	4(13)	014	200
5(5)	224	700	5(17)	004	100
6(8)	124	500	6(18)	003	75
7(10)	024	300	7(19)	002	50
8(11)	023	275	8(20)	001	25
9(12)	022	250			
10(14)	012	150			
11(15)	011	125			
12(16)	010	100			

[a]ABC WHERE A=NUMBER OF 200-W LAMPS, B=NUMBER OF 100-W LAMPS, AND C=NUMBER OF 25-W LAMPS. LAMPS 1 THROUGH 6 ARE 200 W EACH, 7 AND 8 ARE 100 W EACH, AND 9 THROUGH 12 ARE 25 W EACH.

[b]NUMBER IN PARENTHESES IS RANK OF SEQUENCE LEVEL FROM 1 (BRIGHTEST) TO 20 (FAINTEST) FOR ALL 20 TEST LEVELS.

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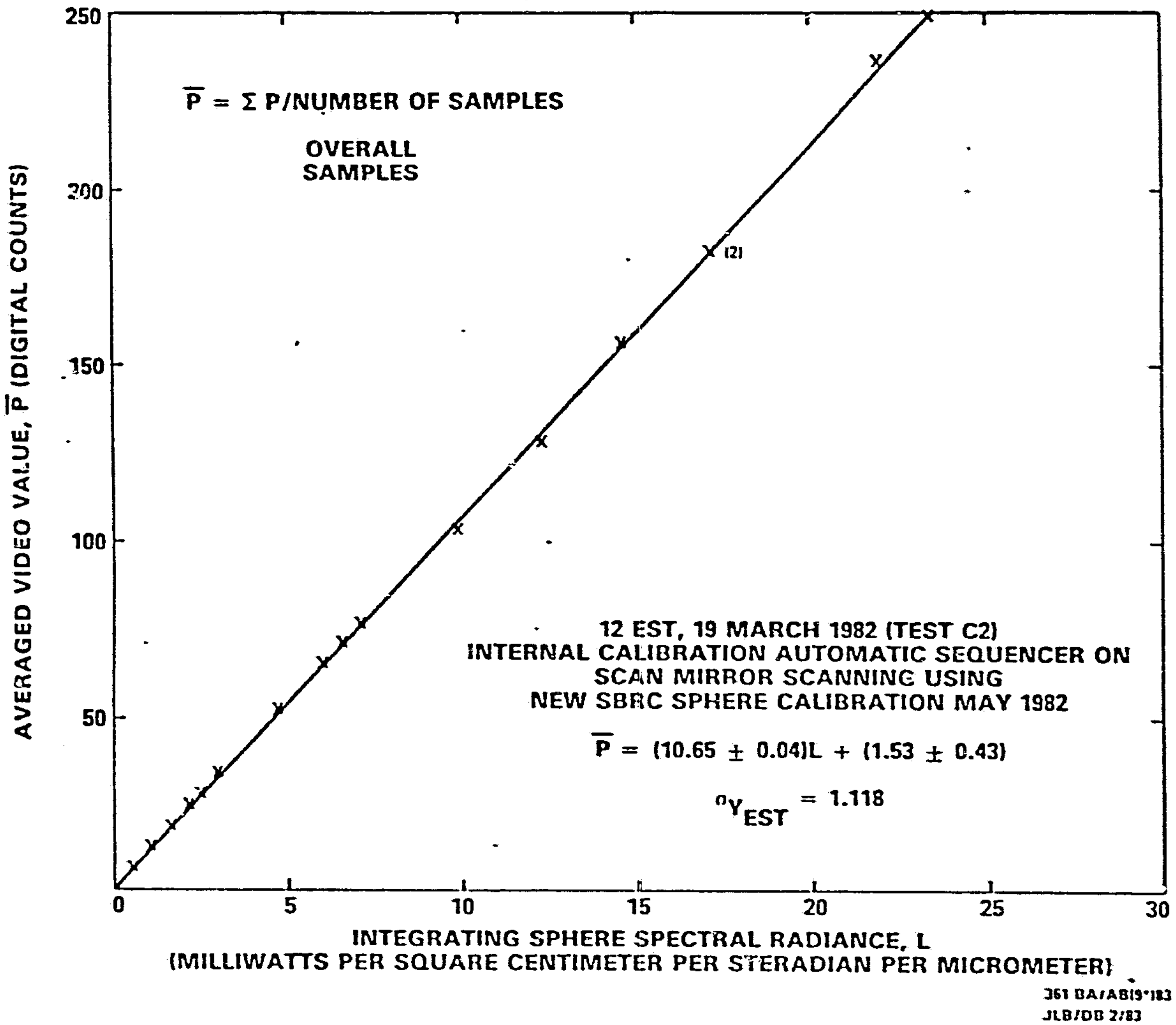
FIGURE 10

ILLUSTRATIVE TM/PF RADIOMETRIC ABSOLUTE DETECTOR CALIBRATION FOR CHANNEL 9 OF BAND 3 (624-693 nm)



The SNR at each level (k) is also computed from the averaged digital count ($\overline{P}_k$) and the standard deviation (σ_k):

$$SNR_k = \frac{\overline{P}_k}{\sigma_k}$$

A least-square linear regression is used to obtain SNR as a function of $\overline{P}$.

The input radiance to the TM is computed by combining the output of the IS(122) for a given configuration of lamps (radiance level) with the measured response of the TM in each band. This is given by

$$L_\lambda(B) = \frac{\int_{\lambda_1}^{\lambda_2} L^j_{sphere}(\lambda) \cdot R(\lambda)\, d\lambda}{\int_{\lambda_1}^{\lambda_2} R(\lambda)\, d\lambda} .$$

where

$L_\lambda(B)$ = spectral radiance in a particular TM band

$L^j_{sphere}(\lambda)$ = output of the sphere at radiance level j

$R(\lambda)$ = spectral response of the TM band as a function of wavelength

The integration is done from wavelength λ_1 to λ_2 for a particular TM band. The critical parameters in the calibration are alignment and separation between the IS(122) and the TM, the TM scan mirror operating mode (locked or scanning), and the sphere output to the TM in each band at each radiance level ($L_\lambda(B)$ above). The alignment of the TM with the IS(122) is shown schematically in Figure 11. The distance marked A in the figure has varied widely in the different tests performed to calibrate the TM. Table 4 gives

FIGURE 11

PLACEMENT OF THE TM AND THE IS(122) ILLUSTRATING THE NEED FOR GOOD ALIGNMENT WHEN THE DISTANCE OF A IS LARGE

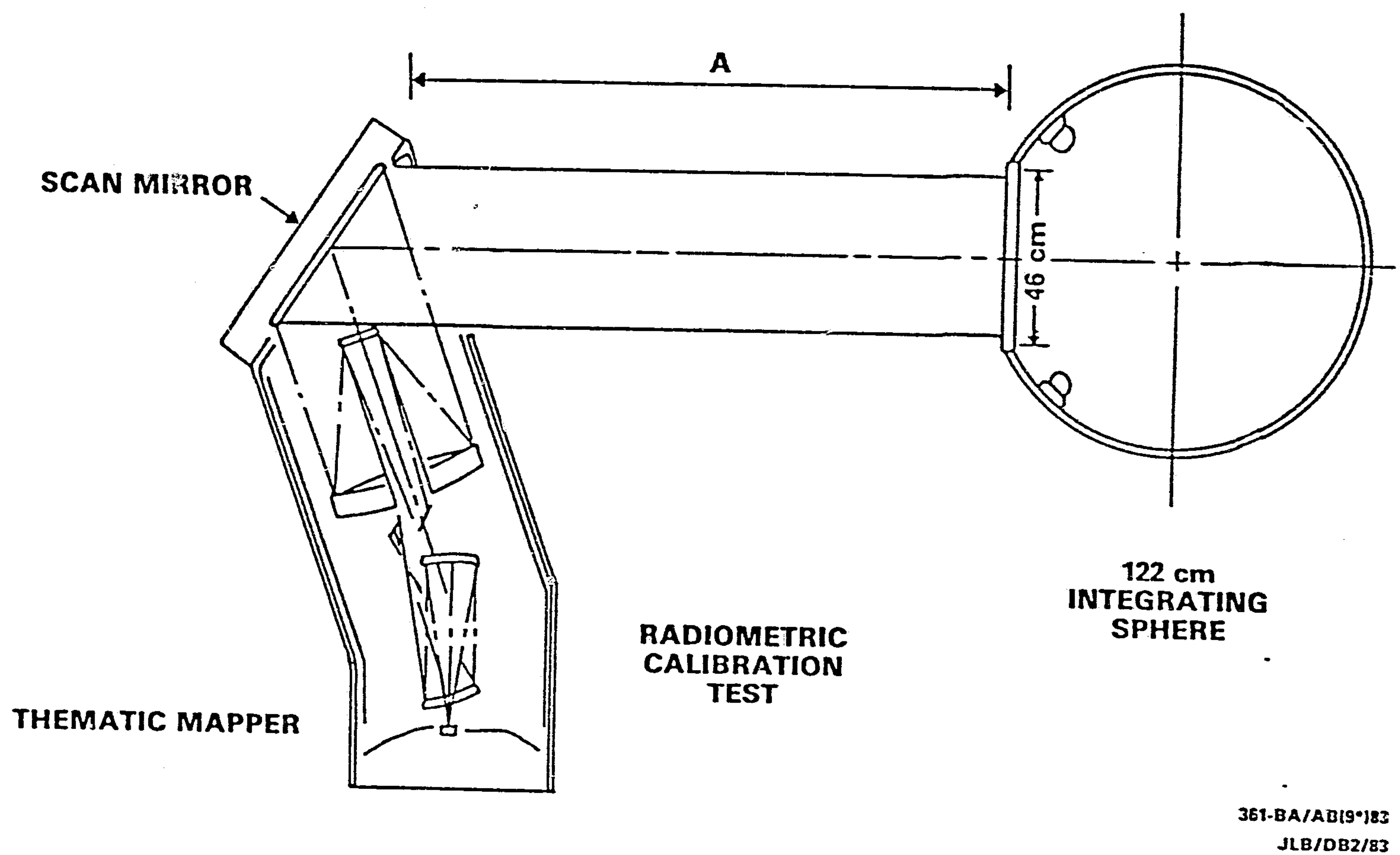


TABLE 4

DATES OF CALIBRATION OF THE TM WITH THE IS(122)

TEST[a] DESIGNATION	TEST DATE	SEPARATION DISTANCE (METERS)	LOCATION[c]
A	29 AND 30 JUNE, 1981	5.2	HAC/SBRC
B[b, d]	3 NOVEMBER, 1981	7.6—9.1	GE/VF
C[d]	19 MARCH, 1982	3.7—4.3	GE/VF

[a] ALL HAC AND GE DOCUMENTS HAVE USED THE HUGHES "AC02" DESIGNATION FOR IS TESTS. REFERENCES: TEST A, OSGOOD AND LANSING (1981); TEST B, YOUNG (1982); AND TEST C, UNDOCUMENTED.

[b] BANDS 1 THROUGH 4 ONLY.

[c] HAC/SBRC, HUGHES AIRCRAFT COMPANY, SANTA BARBARA RESEARCH CENTER, SANTA BARBARA, CA; GE/VF, GENERAL ELECTRIC, VALLEY FORGE, PA.

[d] SCAN MIRROR WAS ALLOWED TO SCAN THE SPHERE APERTURE. DURING TEST A, THE SCAN MIRROR WAS LOCKED.

NOTE: TEST A CONSISTED OF TWO SEPARATE CALIBRATION RUNS WITH THE CFPA TEMPERATURE AT −179.8° AND −168.5°C (TESTS A1 AND A2, RESPECTIVELY). TEST C CONSISTED OF THREE SEPARATE RUNS ($T_{CFPA} \sim -177$°C): SCAN MIRROR LOCKED (TEST C1) IC AUTOMATIC SEQUENCER ON, SCAN MIRROR SCANNING (IC A.S. ON) (TEST C2), AND MIRROR SCANNING (IC IN BACKUP MODE) (TEST C3). NEW SBRC SPHERE CALIBRATION (MAY 1982) USED FOR ALL C TESTS.

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the dates, the separation distances (A) between the TM and the IS(122), and a letter designation for each test. Table 5 shows the variability in the measured channel gain in each test. The alignment of the TM with the IS(122) is particularly important at the larger separations if the scan mirror is locked in place. The IS(122) aperture is 46 centimeters, which is illuminating the 41-centimeter TM aperture; at a separation of 5.2 meters, the spread of the TM spectral bands along the scan is 3 centimeters at the prime focal plane. This leaves a maximum travel of 2 centimeters during which all detectors of each band (1 through 5 and 7) may simultaneously see the same part of the IS(122). If the scan mirror is locked in place, the alignment thus becomes critical. This is not the case if the scan mirror is allowed to move. Test procedures originally required the scan mirror to be locked at midscan; these were changed after the June 1981 test. Both locked and scanning modes were used in March 1982. To ensure that the peak response is actually measured, the test procedures with the scan mirror operating may also require that the raw output from the sphere be searched for the largest response and then fitted by a second-order polynomial. This has not been a part of the calibration procedure, however, and may have to be included to reduce the error if it is found that the output of the IS(122) as seen by the TM is not sufficiently flat. The test procedure may thus be summarized as follows:

1. Select an external radiance source as standard (IS(122))

2. Determine the characteristics and output of the external standard

3. Adjust trim resistors for each detector in the TM to obtain the correct dynamic range

4. Measure the TM performance at various external radiance levels and cooled focal plane temperatures

5. Determine the gain, offset, dynamic range, and SNR of each detector

6. Transfer the calibration from the detectors to the IC

7. Use the TM to calibrate other external calibrators for use when the IS(122) is unavailable (as in vacuum chamber testing)

8. Conduct spectral matching tests for band-to-band comparisons

TABLE 5

SUMMARY OF AVERAGE GAIN CHANGES IN PERCENT BY TEST REFERENCED TO TEST C2

BAND		TEST					
		A1	A2	B	C1	C2	C3
1	ODD	5.28	5.22	1.17	0.82	—	−0.03
	EVEN	4.91	4.83	1.13	0.91	—	−0.02
	ALL	5.09	5.03	1.15	0.86	—	−0.02
2	ODD	0.48	0.24	−1.95	−0.29	—	−0.63
	EVEN	0.45	0.21	−2.01	−0.32	—	−0.67
	ALL	0.47	0.22	−1.98	−0.30	—	−0.65
3	ODD	0.45	0.20	−2.22	−0.32	—	−0.55
	EVEN	0.23	−0.01	−2.29	−0.23	—	−0.51
	ALL	0.34	−0.09	−2.25	−0.28	—	−0.53
4	ODD	3.91	4.00	3.75	0.62	—	0.08
	EVEN	3.78	3.88	3.69	0.61	—	0.06
	ALL	3.85	3.94	3.72	0.62	—	0.07
5	ODD	5.45	4.75	—[b]	−0.17	—	−0.02
	EVEN	5.45	4.78	—	−0.28	—	−0.18
	ALL	5.45	4.77	—	−0.23	—	−0.11
7	ODD	3.59	3.09	—[b]	0.01	—	−0.12
	EVEN	3.47	4.77	—	0.06	—	−0.09
	ALL	3.53	3.93	—	0.03	—	−0.11

[a]GAIN CHANGE DEFINED AS: VALUE=100%x(CURRENT−REFERENCE)÷REFERENCE.

[b]NO BANDS 5 AND 7 DATA TAKEN DURING TEST B.

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CALIBRATION TRANSFER TO THE IC

The IC is used mainly for measuring relative performance in flight. External calibrators can be used only on the ground. To maintain good radiometric accuracy, it is important to carefully calibrate the IC using a known standard. Furthermore, the behavior of the TM as a function of temperature and age should be well understood so that IC measurements can be corrected, because there is no way to obtain absolute calibration in flight.

The function of the calibration transfer is to provide reference radiance levels for the IC in different operating modes. These reference data are then used to calibrate in-orbit scene data and to monitor the health of the detectors during postlaunch operation. The procedures used to process the raw transfer data should be the same as those proposed for operational postlaunch ground processing. To transfer the absolute IS(122) calibration from the TM detectors to the IC, the raw IC calibration pulse must be extracted from the telemetry stream; a suitable pulse integration method must be applied to all detector data; and all integrated values for a particular lamp configuration must be averaged, excluding certain scans near lamp state changes. The actual algorithms used are the same as the SCROUNGE ground radiometric processing procedures discussed in the next section. The lamp state values may then be converted from averaged digital counts ($\bar{P}$) (output from the TM) to effective spectral radiance using the calibration parameters (G and O) determined from the IS(122) calibration (Barker, 1984).

Regardless of the IC operational mode, all eight lamp states for all detectors must be processed through the eight steps mentioned previously.

GROUND RADIOMETRIC PROCESSING PROCEDURES

From launch through July 1983, TM image data were processed using the IC with the SCROUNGE processing algorithms. In July 1983, an early version of TIPS became available. The important features of the SCROUNGE algorithms will be described here, and the resulting products will be mentioned. TIPS will be discussed only in terms of its differences from SCROUNGE.

The use of the IC to radiometrically calibrate image data from the reflective bands involves six steps:

1. Extracting calibration minor frames

2. Integrating a pulse to obtain a pulse height

3. Averaging pulse heights belonging to a state and identifying the IC state

4. Obtaining detector gains and offsets by regression analysis of observed pulse averages versus nominal values

5. Adjusting gains and offsets of channels within a band to achieve a common radiance range

6. Balancing relative grey levels using histogram normalization (optional)

During the SCROUNGE era, only the minor frames (mf) falling within a 148-mf window are examined for pulse extraction. If part of the pulse falls outside the window, the integrated pulse value is reduced. The pulse extraction window is located at a fixed distance from the start of the line. The distance is the same for all channels but different for forward and reverse scans. A detailed history of the location of calibration windows is given in Barker et al. (1984b). SCROUNGE integrates pulses by using the Hughes algorithm (Figure 12), which consists of the following steps:

1. Locate pulse maximum

2. Move outward from the maximum to locate pulse edges that are 40 percent of the maximum value

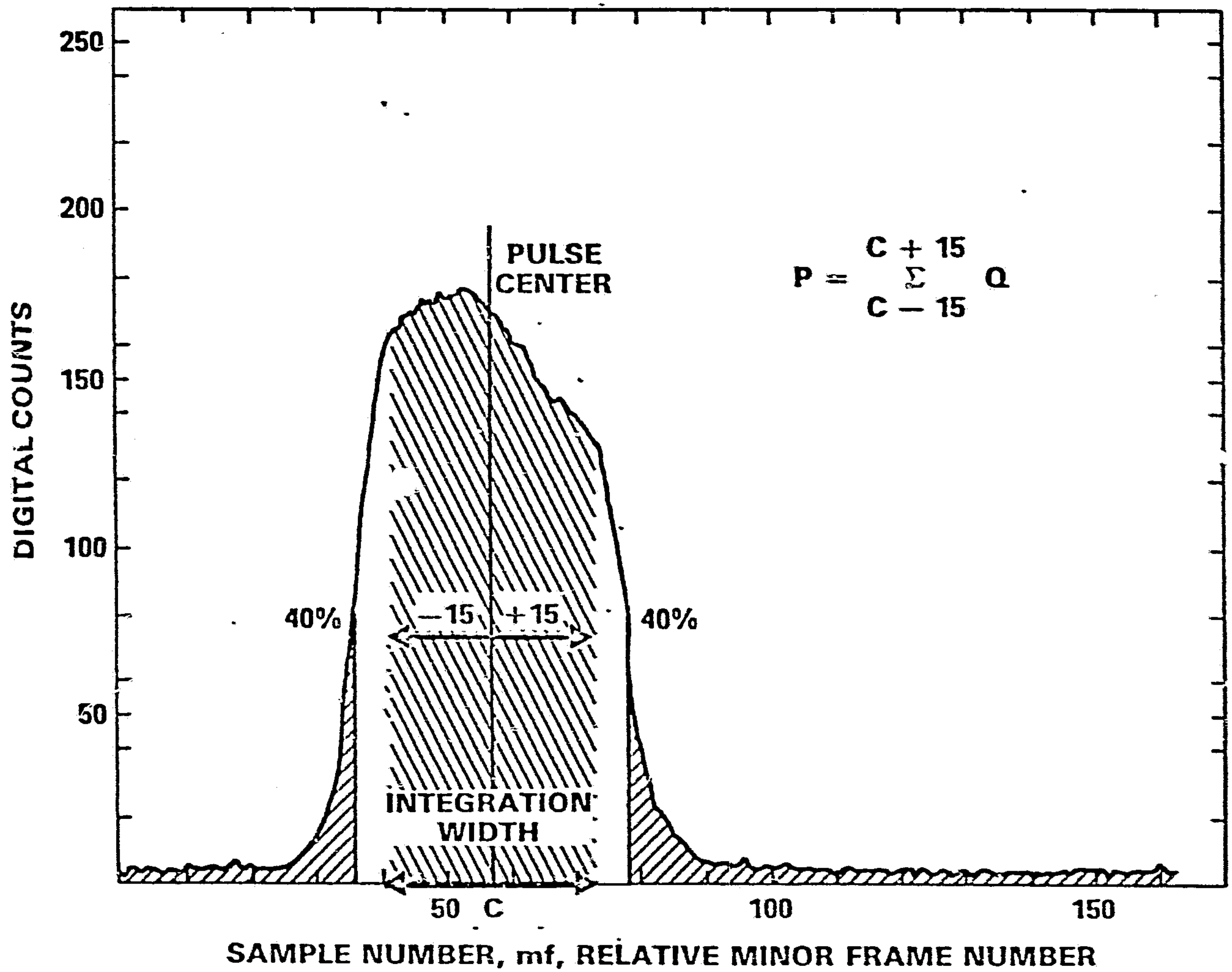
3. Define pulse center as the midpoint of the line segment defined by the pulse edges

4. Average 31 points (pulse integration width) about the pulse center to obtain the pulse height

Pulse averaging involves identifying an IC state transition, determining which scans between transitions to include in the average, averaging the pulses from selected scans to obtain the averaged pulses $\overline{P}(\ell,C)$, and associating $\overline{P}(\ell,C)$ with an IC state. In SCROUNGE, pulse heights from forward and reverse scans are averaged together. A transition occurs when the pulse height of a scan differs from the pulse height of the previous scan by more than three digital counts. The first 25 scans following a transition are ignored (Figure 9); the remaining scans, preceding the next transition, are averaged to determine $\overline{Q}$. The average pulse is associated with the IC state having the closest nominal averaged pulse value. Data from each of the 96 reflective channels are processed separately. When

FIGURE 12

POSTLAUNCH RADIOMETRIC CALIBRATION — TM LANDSAT-4 HUGHES ALGORITHM



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51 channels agree on an IC state, the IC state is considered identified and is assigned to all channels.

Gain (G(C)) and offset (O(C)) are determined for each channel by a linear unweighted regression of counts versus nominal counts using all eight IC states. A radiance range in digital counts common to all the channels within the band (RMAX-RMIN) is determined for each band. Gains and offsets are then normalized so that values obtained for each channel lie within the common range.

First RMAX and RMIN are used to determine postcalibration gain ($G^o(B)$) and offset ($O^o(B)$):

$$G^o(B) = \frac{QMAX}{RMAX-RMIN}$$

$$O^o(B) = \frac{QMIN - QMAX*RMIN}{(RMAX-RMIN)}$$

where QMAX is the full-scale digital value (255) and QMIN is the minimum digital value (0). Normalized gain $NG_{IC}(C)$ and normalized offset ($NO_{IC}(C)$) for each channel (C) in the band are then determined as follows:

$$NG_{IC}(C) = G(C)/G^o(B)$$

$$NO_{IC}(C) = O(C) - NG_{IC}(C) * O^o(B)$$

As a result of this approach, adjusted count values for particular channels that lie outside the common range are simply set to lie at the maximum or minimum of the range as appropriate.

Histogram normalization involves the following steps for each band:

1. Histograms are obtained for each channel.

2. The histograms for all the channels in the band are combined to form an average histogram.

3. A new gain (N'G) and a new offset (N'O) for each channel are derived by adjusting $NG_{IC}(C)$ and $NO_{IC}(C)$ so that the channel histogram will have the same average (μ) and standard deviation (σ) as the band average histogram:

$$N'G = NG_{IC}(C) * \frac{\sigma_i}{\overline{\sigma}}$$

and

$$N'O = NO_{IC}(C) - N'G * \overline{\mu} - \frac{\overline{\sigma} * \mu_i}{\sigma_i}$$

where μ_i and σ_i are the respective mean and standard deviation for the histogram for channel i before normalization.

4. The new gains and offsets are then used to produce a radiometric lookup table (RLUT) for each channel:

$$RLUT_{ij} = \frac{P_j - N'O}{N'G}$$

where $RLUT_{ij}$ is the value in the lookup table corresponding to an initial value P_j in channel C.

5. The image is radiometrically corrected using the RLUT.

Uncalibrated image data are available on a computer-compatible tape (CCT) known as the CCT-BT tape. This tape also contains the initial gains and offsets (prior to range adjustment and histogram normalization) for each channel. CCT-BT tapes generated after April 1983 also contain the histogram-normalized gains and offsets. The CCT-AT tapes contain the radiometrically corrected image. A final product containing radiometrically and geometrically corrected

resampled data is also available. These digital products are described in detail in Barker and Gunther (1984).

TIPS is a flexible system that provides three options: the use of nominal gains and offsets, the use of nominal gains and scene-specific background for offsets, and the use of the IC to determine gains and offsets. In each case, the use of histogram normalization is optional. Differences between the SCROUNGE and TIPS processing algorithms are highlighted below.

In general, the TIPS algorithms produce more stable results and handle noise in the calibration data better. Specifically, TIPS will examine the entire shutter flag part of the scan to extract the calibration pulse, thereby eliminating the risk of clipped pulses. The TIPS pulse integration method, THRESH, uses a wider pulse integration width of 65 minor frames. The pulse averaging algorithm uses information from several scans (currently 10) to locate IC state transitions. Out-of-range scans (deviating by a predefined amount from the average of the stable part of the current data) as well as scans on both sides of a transition are not included in the averaged pulse value $\bar{P}$. In the regression analysis, background data from each scan as well as the 000 IC state value are used. Each pulse average used in the regression is weighted based on the number of scans contributing to the pulse average and the standard deviation of the average. The one aspect of SCROUNGE that is probably safer than TIPS is in IC state identification. Unlike SCROUNGE, TIPS uses only one or a small number of channels to identify the IC state.

SUMMARY

The TM radiometric subsystem observes radiance reflected from the Earth in six reflective bands: 0.45 to 52 μm, 0.52 to 0.60 μm, 0.63 to 0.69 μm, 0.76 to 0.90 μm, 1.55 to 1.75 μm, and 2.08 to 2.35 μm and one thermal band at 10.4 to 11.6 μm. Each band comprises 16 detectors that create 16 raster lines as the ground is scanned in both forward and reverse directions along the crosstrack. The IC consists of three miniature tungsten filament lamps for the reflective bands, a blackbody for the thermal band, and a flex pivot-mounted resonant shutter. The IC inserts reference radiance levels just ahead of the spectral filters of each band at the prime focal plane while obscuring the Earth from the detectors.

Prior to launch, the TM channels were absolutely calibrated with a secondary standard 122-centimeter integrating sphere. The objectives of the calibration procedure were to determine absolute channel gain and to characterize relative radiometric accuracy, within-band accuracy, SNR, and dynamic range. The TM channels were used to calibrate the IC.

The use of the IC to calibrate TM data in the ground processing system consists of pulse extraction, pulse integration, pulse averaging, IC state identification, linear regression analysis, adjustment of the detectors within a band to a common range, and histogram equalization. The important features of the SCROUNGE radiometric calibration system, which was operative through July 1983, are as follows:

- Pulse integration width is 31 minor frames wide.
- Forward and reverse scans are processed together.
- The first 25 scans following an IC state transition are excluded from the pulse average. No scans are skipped before a lamp transition.
- IC state identification is made through comparison with nominal values. All channels are checked with the results determined by agreement of the majority.
- Linear regression analysis is unweighted and includes all eight IC states.
- In histogram equalization, the mean and standard deviation of each channel are adjusted to conform with the band average.

The TIPS radiometric calibration process, which replaced SCROUNGE in July 1983, differs from SCROUNGE as follows:

- Pulse integration width is 65 minor frames.
- In pulse averaging, scans on both sides of an IC state transition are skipped.
- Only a small preselected group of channels are checked to identify the IC state.
- Linear regression is weighted. Background data from each scan are used as well as the eight IC states. In band 4, the 111 state, which is saturated, is not used in the calibration.

RECOMMENDATIONS

Brief recommendations are given below; expanded recommendations are given in Barker (1984). An improvement in both relative and absolute accuracy of the radiometric calibration can be achieved by modifying the calibration procedure. Of course, any change in the postlaunch procedure would require a reprocessing of the prelaunch absolute calibration data using the modified algorithms. From the results presented in Barker et al. (1984b), it is clear that forward and reverse scan data should be processed separately. A wider pulse integration width would reduce the noise in the averaged pulse values. A wider pulse extraction window or a pulse extraction window that shifted with channel number would eliminate pulse truncation and permit the use of a wider integration width. The use of background data from each scan line for calibration of that scan would probably be preferable to applying the average background observed during the lamps-off (000) state to all the scans in a scene. When applying background data to an image line, however, care must be taken to use background data that have not been altered by dark current (DC) restore subsequent to the time the image was taken. Barker et al., 1984, presents additional recommendations for postlaunch procedures; Barker et al., 1984a, recommends improvements for the absolute calibration procedures.

REFERENCES

Barker, John L., "Relative Radiometric Calibration of Landsat TM Reflective Bands," PROCEEDINGS, LANDSAT-4 SCIENTIFIC CHARACTERIZATION EARLY RESULTS SYMPOSIUM, Goddard Space Flight Center, Greenbelt, Maryland, April 1984

Barker, J. L., D. L. Ball, K. C. Leung, and J. A. Walker, "Prelaunch Absolute Radiometric Calibration of the Reflective Band on Landsat-4 Protoflight Thematic Mapper," PROCEEDINGS, LANDSAT-4 SCIENTIFIC CHARACTERIZATION EARLY RESULTS SYMPOSIUM Goddard Space Flight Center, Greenbelt, Maryland, April, 1984a

--, R. B. Abrams, D. L. Ball, and K. C. Leung, "Characterization of Radiometric Calibration of Landsat-4 TM Reflective Bands," PROCEEDINGS, LANDSAT-4 SCIENTIFIC CHARACTERIZATION EARLY RESULTS SYMPOSIUM, Goddard Space Flight Center, Greenbelt, Maryland, April 1984b

--, F. J. Gunther, R. B. Abrams, and D. L. Ball, "TM Digital Image Products for Applications," PROCEEDINGS, LANDSAT-4 SCIENTIFIC CHARACTERIZATION EARLY RESULTS SYMPOSIUM, Goddard Space Flight Center, Greenbelt, Maryland, April 1984

Duck, K. I., "Revised Thematic Mapper Radiometric Assessment," Goddard Space Flight Center, Greenbelt, Maryland, Internal Memorandum, 1977

Engel, J. C., "Thematic Mapper: An Interim Report on Anticipated Performance" (paper presented at AIAA Sensor Systems for the 80's Conference, Colorado Springs, Colorado, 1980)

Fraser, R. S., "Radiances for Thematic Mapper," Goddard Space Flight Center, Internal Memorandum, 1975

Lansing, J. C., and J. L. Barker, "Thermal Band Characterization of Landsat-4 Thematic Mapper," PROCEEDINGS, LANDSAT-4 SCIENTIFIC CHARACTERIZATION EARLY RESULTS SYMPOSIUM, Goddard Space Flight Center, Greenbelt, Maryland, April 1984.

Lyons, J., D. Fischel, and E. Beyer, "Production and Analysis of the Output Data Products for Landsat-4 in the Engineering Checkout Phase," PROCEEDINGS, LANDSAT-4 SCIENTIFIC CHARACTERIZATION EARLY RESULTS SYMPOSIUM, Goddard Space Flight Center, Greenbelt, Maryland, April 1983

Markham, B., and J. L. Barker, "Spectral Characterization of the Landsat Thematic Mapper Sensors," PROCEEDINGS, LANDSAT-4 SCIENTIFIC CHARACTERIZATION EARLY RESULTS SYMPOSIUM, Goddard Space Flight Center, Greenbelt, Maryland, April 1984

McCullough, A. W., J. T. McLean,, and E. I. Mohr, "Evaluation and Calibration of Some Energy Sources for the Visible and Near Infrared Regions of the Electromagnetic Spectrum," NASA/GSFC, X-622-69-195, 1969

Walker, J. A., "Comparisons of 48SIS Calibrations--NASA and SBRC," Santa Barbara Research Center, HS236-8160, 1982a

--, "48 SIS Calibration Data for GE Post T.V. Test Configuration," Santa Barbara Research Center, HS236-7995, 1982b

APPENDIX - CALIBRATION PULSES

Figures A-1 through A-18 are calibration pulses taken from the March 9, 1982, prelaunch vacuum data. Samples are included for forward and reverse scans, even and odd channels.

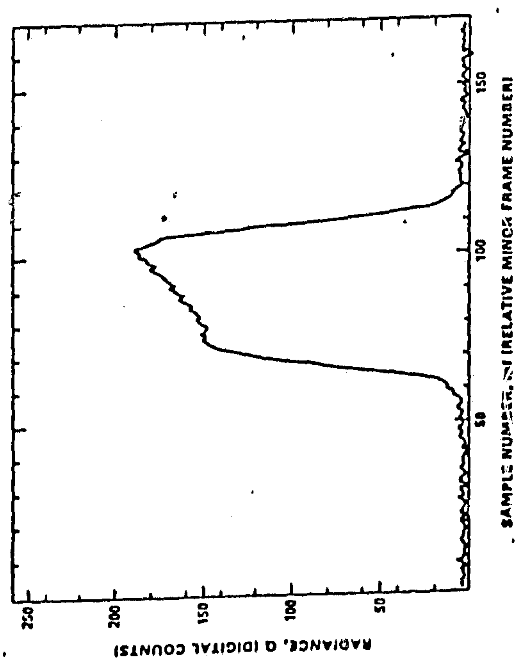

FIGURE A-1
RADIOMETRIC CALIBRATION — TM LANDSAT-4
TM1 C8 FORWARD SCAN, MARCH 9, 1982, VACUUM PRELAUNCH

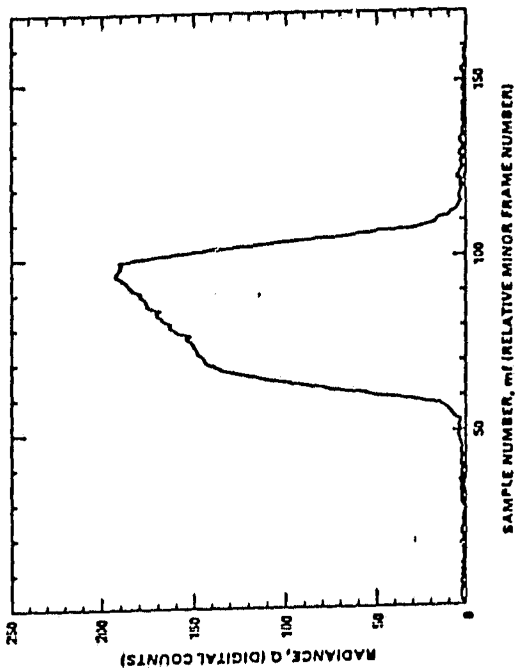

FIGURE A-2
RADIOMETRIC CALIBRATION — TM LANDSAT-4
TM1 C9 FORWARD SCAN, MARCH 9, 1982, VACUUM

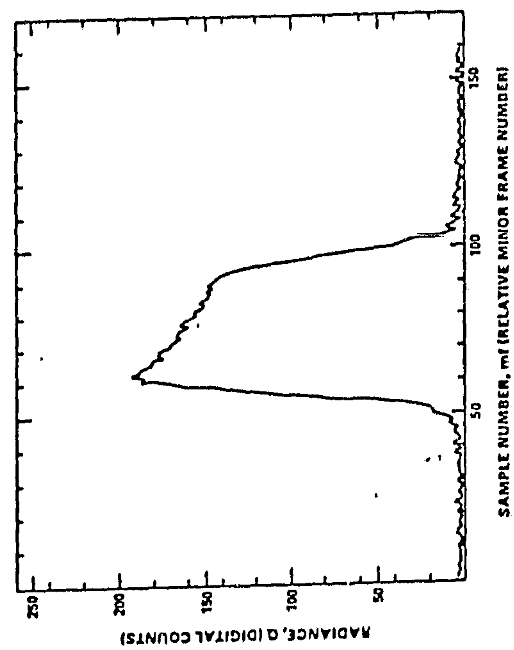

FIGURE A-3
RADIOMETRIC CALIBRATION — TM LANDSAT-4
TM1 C8 REVERSE SCAN, MARCH 9, 1982, VACUUM

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FIGURE A-4.
RADIOMETRIC CALIBRATION — TM LANDSAT-4
TM2 CHANNEL 8 FORWARD SCAN, MARCH 9, 1982, VACUUM

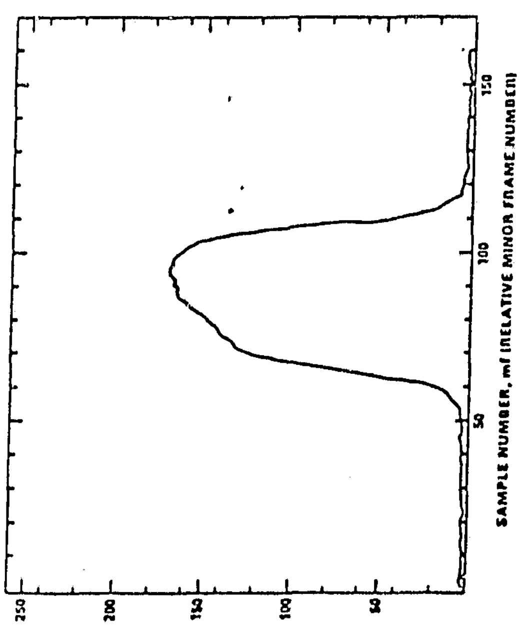


FIGURE A-5
RADIOMETRIC CALIBRATION — TM LANDSAT-4
TM2 C8 FORWARD SCAN, MARCH 9, 1982, VACUUM

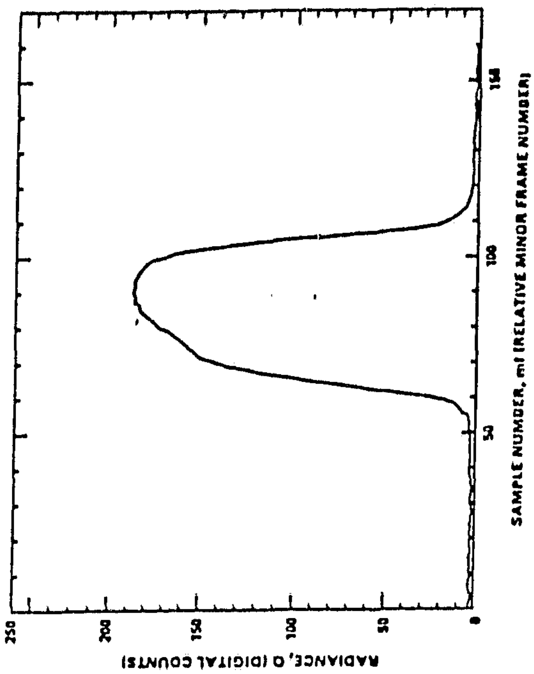
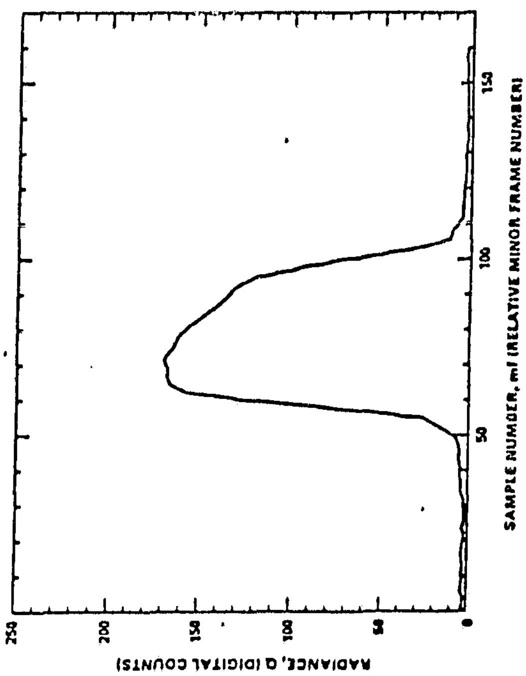


FIGURE A-6
RADIOMETRIC CALIBRATION — TM LANDSAT-4
TM2 C8 REVERSE SCAN, MARCH 9, 1982, VACUUM



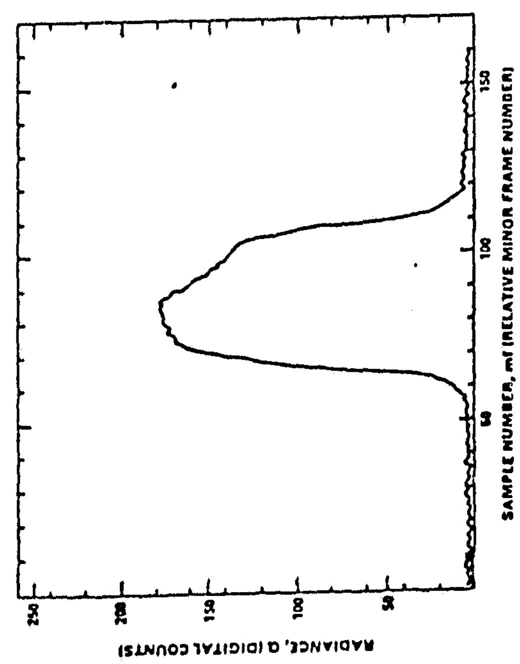


FIGURE A-7
RADIOMETRIC CALIBRATION — TM LANDSAT-4
TM3 CHANNEL 8 FORWARD SCAN, MARCH 9, 1982, VACUUM

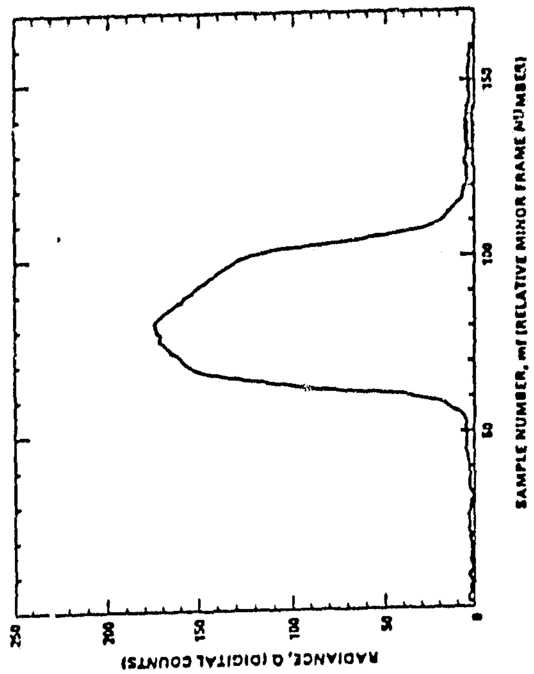


FIGURE A-8
RADIOMETRIC CALIBRATION — TM LANDSAT-4
TM3 C3 FORWARD SCAN, MARCH 9, 1982, VACUUM

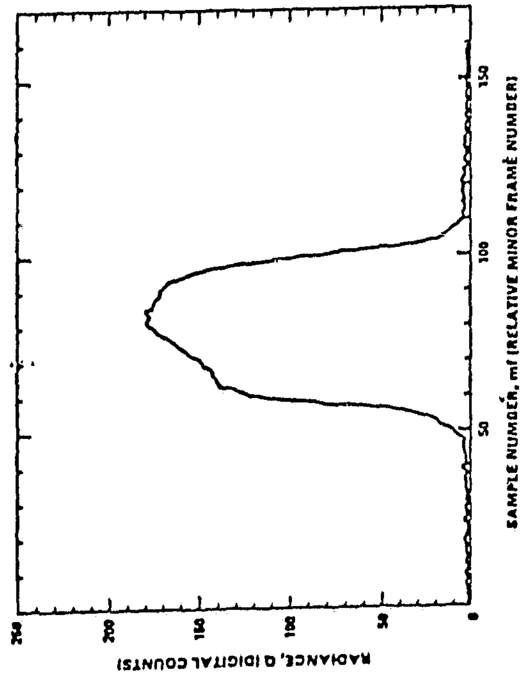


FIGURE A-9
RADIOMETRIC CALIBRATION — TM LANDSAT-4
TM3 C8 REVERSE SCAN, MARCH 9, 1982, VACUUM

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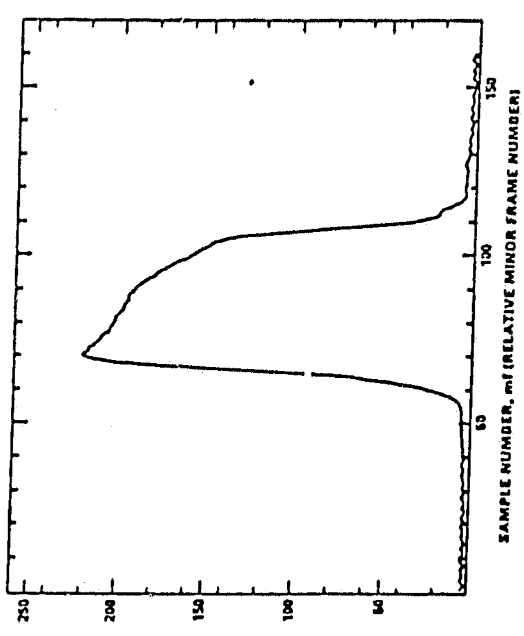


FIGURE A-10
RADIOMETRIC CALIBRATION — TM LANDSAT-4
TM4 CHANNEL 8 FORWARD SCAN, MARCH 9, 1982, VACUUM

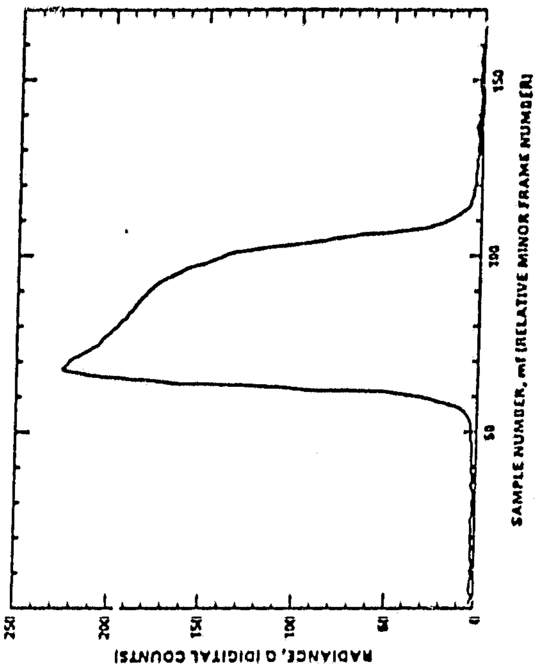


FIGURE A-11
RADIOMETRIC CALIBRATION — TM LANDSAT-4
TM4 C9 FORWARD SCAN, MARCH 9, 1982, VACUUM

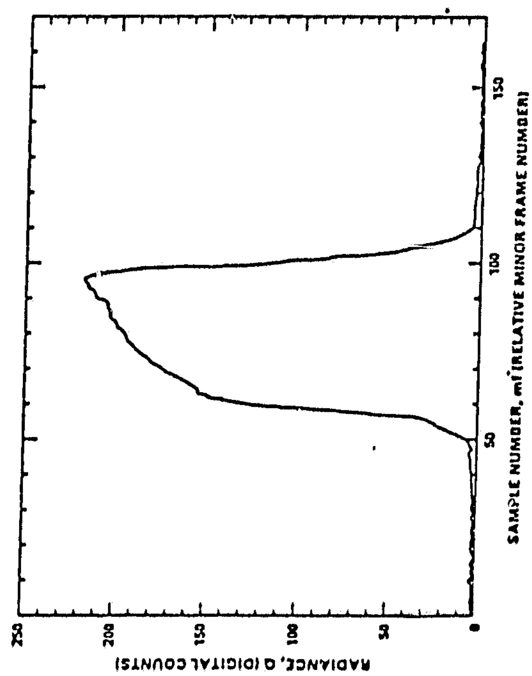


FIGURE A-12
RADIOMETRIC CALIBRATION — TM LANDSAT-4
TM4 C8 REVERSE SCAN, MARCH 9, 1982, VACUUM

FIGURE A-13
RADIOMETRIC CALIBRATION — TM LANDSAT-4
TMS CHANNEL 8 FORWARD SCAN, MARCH 9, 1982, VACUUM

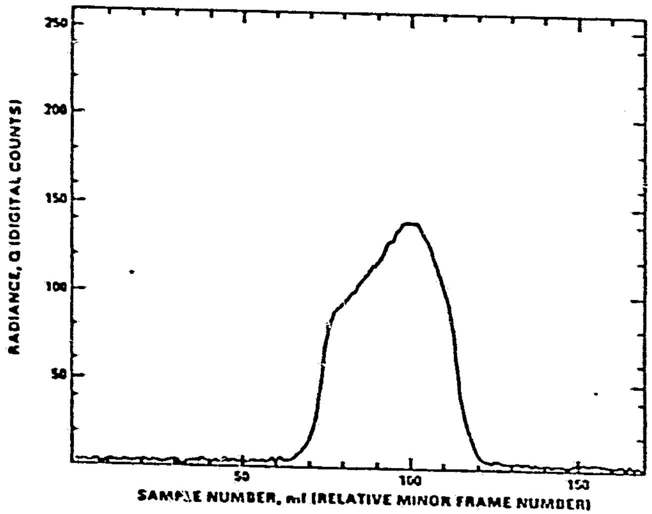


FIGURE A-14
RADIOMETRIC CALIBRATION — TM LANDSAT-4
TMS C9 FORWARD SCAN, MARCH 9, 1982, VACUUM

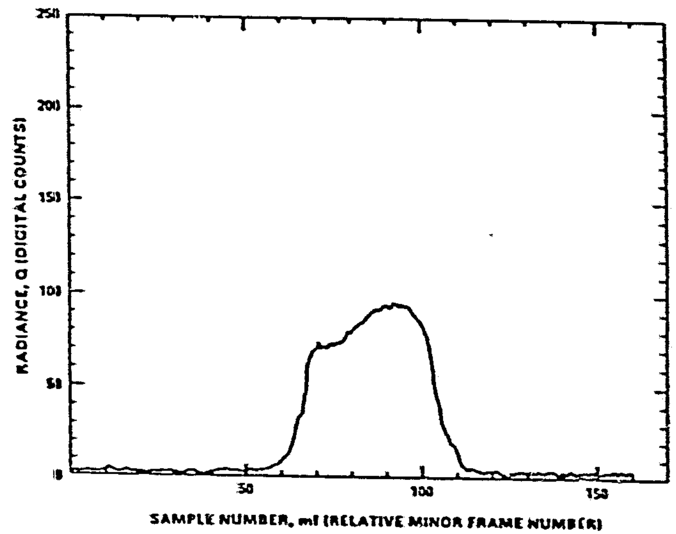
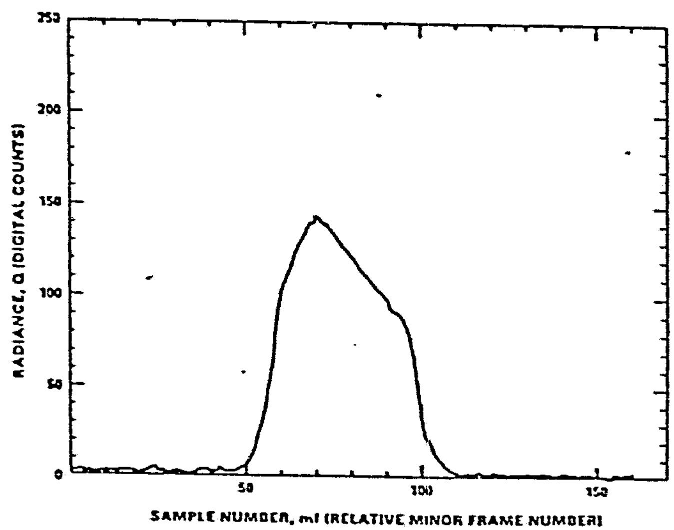


FIGURE A-15
RADIOMETRIC CALIBRATION — TM LANDSAT-4
TMS C8 REVERSE SCAN, MARCH 9, 1982, VACUUM



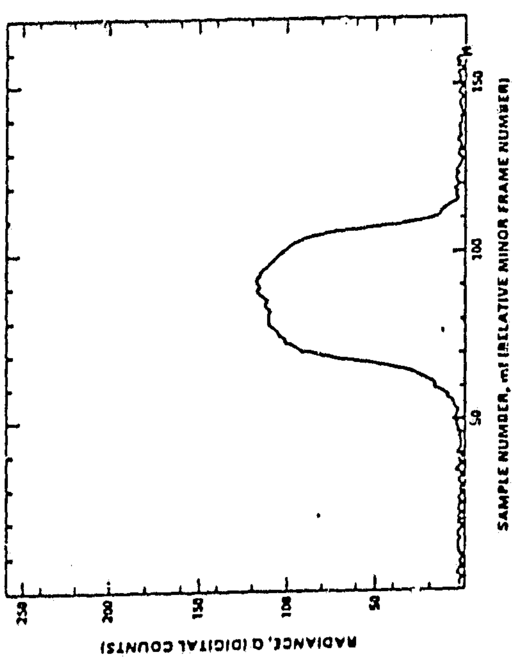


FIGURE A-16
RADIOMETRIC CALIBRATION — TM LANDSAT-4
TM7 CHANNEL 8 FORWARD SCAN, MARCH 9, 1982, VACUUM

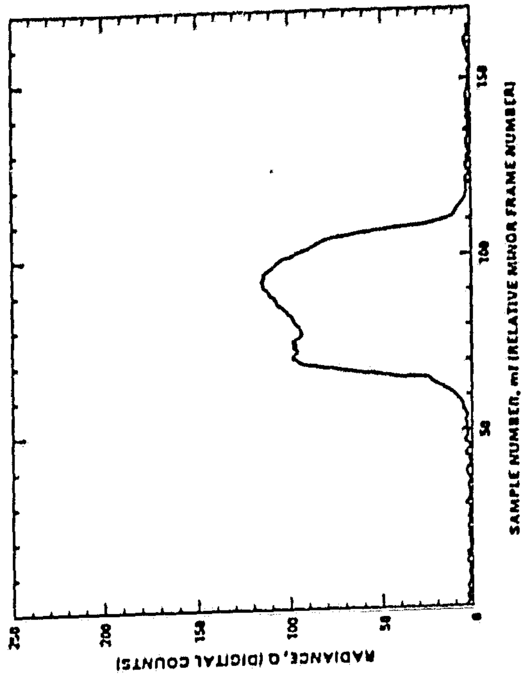


FIGURE A-17
RADIOMETRIC CALIBRATION — TM LANDSAT-4
TM7 C9 FORWARD SCAN, MARCH 9, 1982, VACUUM

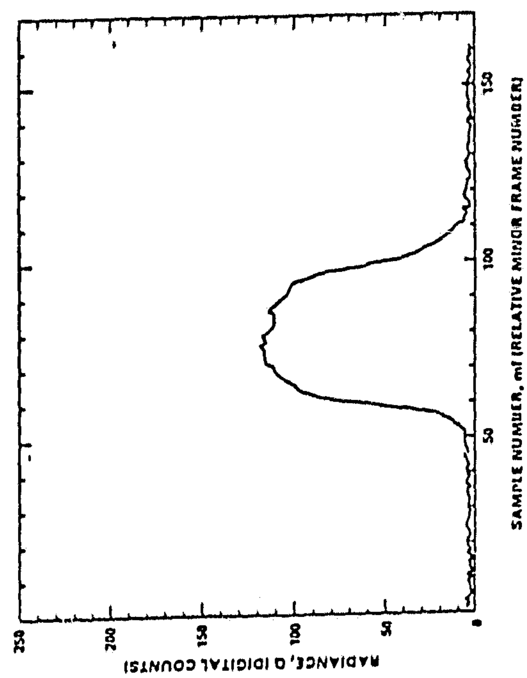


FIGURE A-18
RADIOMETRIC CALIBRATION — TM LANDSAT-4
TM7 C8 REVERSE SCAN, MARCH 9, 1982, VACUUM